

Development of an Automated Fault Detection and Diagnosis tool for AHU's

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Abstract

Heating Ventilation and Air Conditioning (HVAC) system energy consumption on average accounts for 40% of an industrial sites total energy consumption. Studies have indicated that 20 – 30% energy savings are achievable by re-commissioning HVAC systems to rectify faulty operation with savings of over 20% of total energy cost possible by continuously commissioning.

Automated Fault Detection and Diagnosis (AFDD) is a process concerned with automating the detection of faults and their causes in physical systems. AFDD can be used to identify faults in HVAC systems with a view to reducing their energy consumption.

An AFDD tool has been designed and developed to allow the performance analysis of AHU's by utilising knowledge-based principles. Based on an initial alpha testing phase on 12 AHU's across four large industrial pilot sites, in excess of €120,000 of energy savings have been detected by the AFDD tool and verified by site survey.

Keywords

Continuous Commissioning, Fault Detection, HVAC

1. Introduction

The contribution of buildings towards total worldwide energy consumption in developed countries is between 20% and 40%. This is expected to rise by an average rate of 1.5% per annum over the next 20 years [1]. Heating Ventilation and Air Conditioning (HVAC) energy consumption accounts on average for 40% of an industrial sites total energy consumption[2] due primarily to the stringent cleanliness requirements that many of the industrial processes require to be in compliance with international standards[3].

Approximately 50% of a commercial building's energy consumption is associated with HVAC energy consumption [4]. Overall, it is estimated that HVAC energy consumption accounts for 10 – 20% of total energy consumption in developed countries [1].

Buildings rarely perform as well in practice as anticipated during design due to improper equipment selection or installation, lack of commissioning, or improper maintenance [5] to cite but a few reasons. Studies have indicated that 20 – 30% energy savings are achievable by recommissioning HVAC systems to rectify faulty operation [6]. Studies have also demonstrated, using a sample set of over 80 buildings, that continuous commissioning of building systems for peak efficiency can yield savings of an average of over 20% of total energy cost [5]. By coupling the re-commissioning and ongoing commissioning of a HVAC system into one demonstration study, savings of 44% of electricity consumption and 78% of gas consumption over a ten year period have been proven by the International Energy Agency (IEA) Annex 47, DABO Case Study[7], [8].

Building Energy Management Systems (BEMS) are typically the repository of HVAC system data and are now commonly installed in commercial and industrial buildings [9]. The availability of BEMSs offers the potential for innovative commissioning services with lower set-up costs than cases where a BEMS is not present. Automated Fault Detection and Diagnosis (AFDD) is a process which could utilise this BMS generated data to automatically detect faults and their causes in physical systems [10].

1.1 HVAC system management

HVAC systems are typically supervised and maintained by either an onsite facilities team or an offsite third party contractor. Based on the companies involved in this project, the number of Air Handling Units (AHU's) in a typical HVAC system often outnumbers those supervising and maintaining the system by 20 to 1. This means that routine mechanical maintenance is typically carried out only when necessary due to an end user complaint, a machine breakdown or a critical breached alarm limit. The complexity of modern HVAC system control systems also commonly results in onsite personnel not having the required knowledge to root cause issues without costly external consultancy.

Both top down (system level) and bottom up (component level) approaches are common methods of managing HVAC system operation in terms of optimising their energy consumption and achieving other operational targets. The top down approach is growing in its application though it is not yet commonplace. Many industrial and large/multi commercial sites now employ Monitoring & Targeting (M&T) approaches, energy performance

indicators, and performance dashboards to manage site energy consumption. Typically these systems focus on the most significant energy end-uses, of which HVAC is typically one. Structured energy management systems such as those in compliance with En16001 [11] or ISO50001 [12] promote this philosophy of energy management and are growing in their adoption.

The bottom up approach is far more common in practice. This method has developed from breakdown maintenance of key HVAC system components, such as fans and filters; to time based maintenance; to today's common process of monitoring equipment based on its condition and then carrying out maintenance tasks as required.

1.2 BEMS assisted HVAC system monitoring

BEMS systems are commonly used to supervise the performance of HVAC systems, raising alarms when upper or lower limits of operation are breached. However, they do not diagnose the root cause of these alarms. The sheer number of these alarms coupled sometimes with a lack of understanding as to their root cause, can result in maintenance personnel ignoring, or accepting them without due diligence. Furthermore, when no alarm levels are breached, they do not detect underlying faults during what appears to be normal operation of these systems. A typical example is the refrigeration energy wasted by a passing cooling coil control valve, as illustrated in Figure 1 by the drop in temperature across the cooling coil in the Air Handling Unit (AHU) when the control valve is showing closed. This particular example typically goes unnoticed for long periods of time, as it is often possible for the AHU to maintain control of all set-points due either to the availability of hot return or outside air or due to the availability of a heating coil up or downstream to compensate for the temperature drop across the cooling coil.

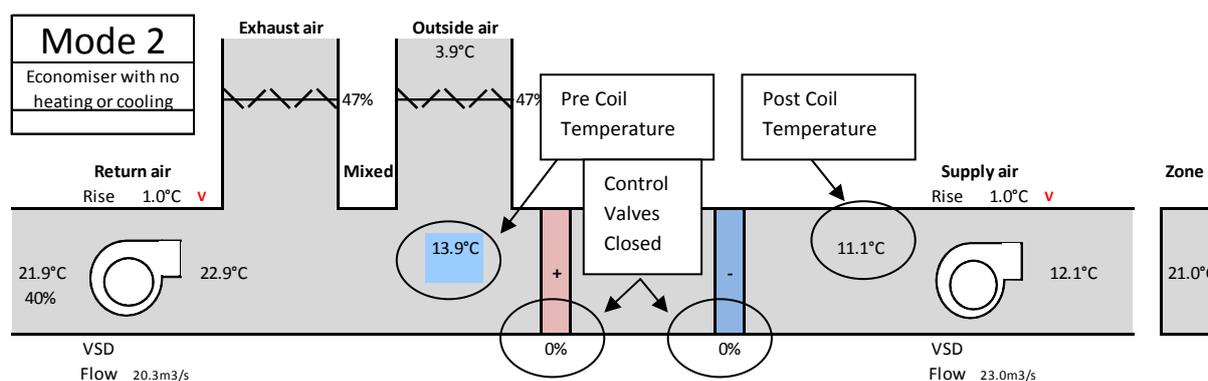


Figure 1: Example of a typically undetected fault in a cooling coil control valve

2. How can an AFDD tool help?

As HVAC systems grow more complex, so too will the maintenance and commissioning processes required to ensure their efficient operation in terms of ensuring adequate air changes and differential pressure balances.

If current trends continue this movement towards more complex systems will result in a more expensive and lengthy maintenance and commissioning processes. As current practices are mostly manual and hence, costly, this will further decrease the likelihood of their ongoing success. For these reasons, the manual nature of maintenance and commissioning is set to change, moving towards an automated method. AFDD is a key means of achieving automated commissioning with many AFDD projects now in the implementation phase from their initial research and development [4]. IEA Annex 47 [7] reviewed the operation of 18 such tools, concluding that automation is still uncommon during the maintenance & commissioning processes, and that future tools should be developed that are easily embedded in existing operational practices. An AFDD tool could hence reduce the cost of both maintenance and commissioning activities, while improving the overall energy efficiency of HVAC systems in the process.

3. AFDD Tool Development

The primary objectives for the AFDD tool being developed as part of this project are:

- Flexibility to work with any BMS
- Flexibility to work with any combination of sensors and components found in typical AHUs;
- To use already available measurement without the need to install additional sensors;
- Capable of evaluating the ongoing performance of AHUs;
- A rapid setup time of the automated FDD tool per AHU;
- A very low number of false positives/negatives in order to build confidence in the tool;
- Quantification and prioritisation of the diagnosed faults

In order for the FDD tool to operate automatically, automated collection of the measured data from AHUs is essential. Figure 2 illustrates the overarching system architecture utilised to develop the AFDD tool.

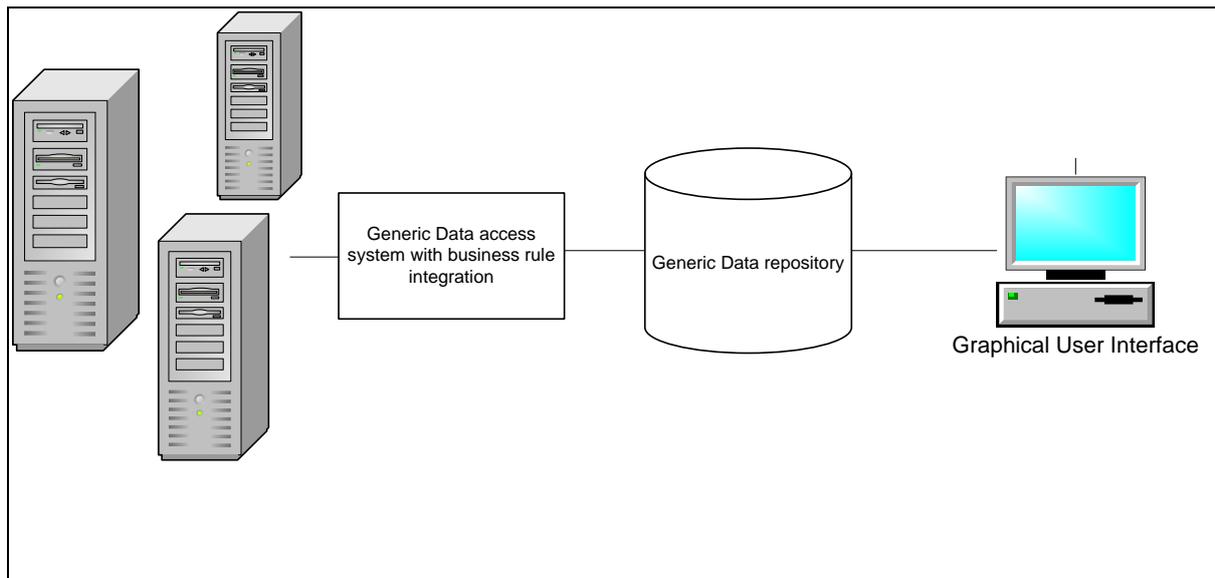


Figure 2: AFDD tool system architecture

3.1 Data Access

There are a number of issues that cause difficulty in obtaining BMS data and transferring it to a database for analysis. Firstly, there are different BMSs in operation across the pilot sites (see Table 1). Each BMS software has its own proprietary method of archiving data. The archiving methods cover a wide range from very primitive (e.g. one comma separated value file for each sensor/or component in which each line in the file corresponds to a daily dump of all of the values stored on the controller) to advanced (e.g. a normalised relational database). Secondly, the issue of getting robust data is exacerbated by the age of the BMS software on some sites. There are often missing values, irregular timestamps and spurious outliers in the data that need to be corrected or removed from the dataset. Thirdly, measured data from the pilot AHUs was not archived at all on many of the sites and needed to be set up as part of initial configuration activity. A generic data access tool was hence developed which could upload BMS data from the client server irrespective of the type of BMS software being utilised.

Table 1: Characteristics of BMS and data acquisition methods on each site.

| Site | BMS manufacturer | Status of data acquisition | Typical frequency of logged data | Logging hysteresis | Method of data acquisition |
|------|------------------|----------------------------|----------------------------------|--------------------|----------------------------|
| 1 | Trend | Daily | 15 minutes | No | Web service application |
| 2 | Satchwell | None | 15 minutes | Unknown | None |
| 3 | Cylon | Daily | 15 minutes | No | Web service application |
| 4 | Cylon | Daily | 15 minutes | No | Web service application |
| 5 | Custom | Weekly | 5 minutes | No | Custom tool |
| 6 | Honeywell | Manual | 15 minutes | Yes | Manual |

3.2 Generic Data

Once uploaded via the data extraction tool, the data had to be parsed to ensure it was generic across all sites. As there was no common naming convention used across all of the BMSs, each sensor/component id tag on the BMS has to be mapped to a particular sensor/component in the database format. The naming convention for each recorded value is then standardised within both the database and the AFDD tool so that different AHUs can easily be compared at a glance. Next, all of the values are converted to a single format for clarity and ease of use across all sites and AHUs. Then, all data is averaged into hourly bins, and fault diagnosis is performed on these hourly values. This is an attempt to smooth out variability in the data due to the dynamic nature of the processes in the AHU. Finally, the processed measured data for each site is then stored in a remotely hosted relational database management system (RDBMS) using MySQL. Static information about each AHU is also required in addition to the measured BMS data, acquired during an initial site survey.

3.3 Fault Identification

Correct identification of the mode of operation of an AHU is critical to identifying how each component should operate, and therefore, critical to performing FDD. Approaches to date have focused on determining the operating mode of the AHU by identifying the actual operating mode from the outside air damper position, cooling and heating coil valve positions

[13–15]. The tool described in this paper incorporates this approach but with some additions to increase effectiveness.

The business layer of the AFDD tool was developed from the APAR rule set [13] with the following modifications:

- Expansion to account for other possible configurations of components and sensors:
 - Frost coils;
 - Reheat coils;
 - Off coil temperature sensors;
 - Before and after fan temperature sensor positions.
- Expansion to account for faults that are apparent when the AHU is off:
 - Open valve positions;
 - Unusually high or low off coil air temperatures.
- Addition of virtual temperature data:
 - The temperature before or after a fan using an estimate for the rise in temperature across the fan
 - The mixing box temperature
 - The average outside air temperature.
- Rearrangement to account for the ideal mode of operation
- Rearrangement to account for the an improved error threshold approach

A client side side application performs the mode checks, calculates the virtual values, applies the business layer rules, and stores the results in the database. The business layer has been designed so that it can be conveniently broken down into categories, several examples of which are described in Figure 3.

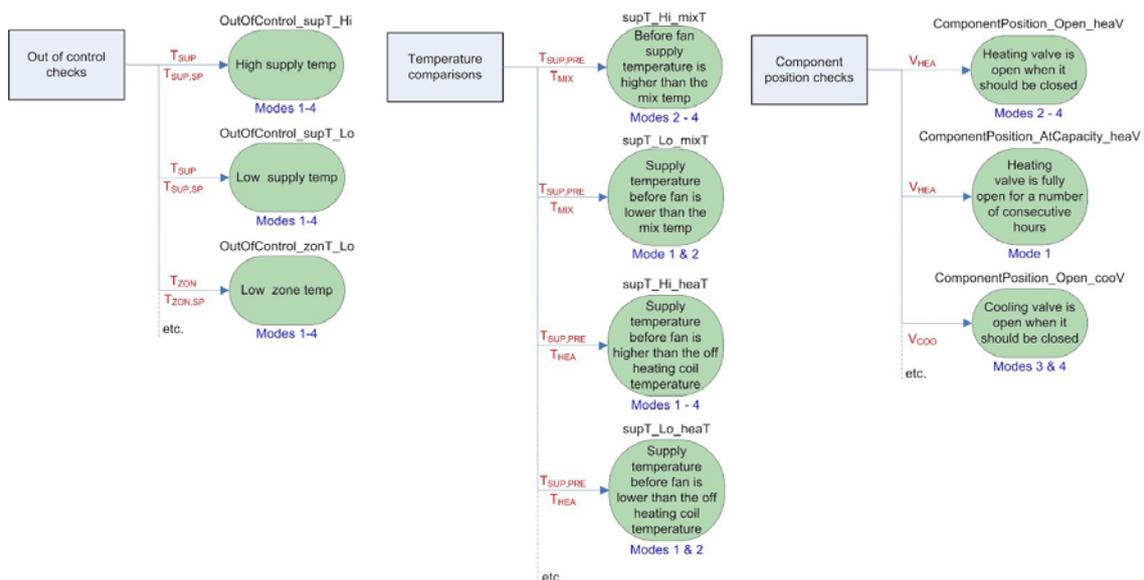


Figure 3: Examples of the business rules

3.4 Improving Fault Identification Accuracy

A key issue identified in the early phase of this project was the use of a single, heuristically defined error threshold value that was applied to all of the rules. The purpose of this error threshold is to reduce false positives: where a fault is identified by the tool but none is present in the AHU. This error threshold is intended to account for all of the inaccuracies in measurements due to sensor error, sensor location, whether the measurement is taken using an averaging or point sensor, and the dynamic nature of AHU operation.

A major issue with previous approaches is that the actual error associated with each rule is dependent on the number and type of measurements used in a particular rule. For example, a rule using just one measurement from an averaging temperature sensor should have a lower error threshold than a rule using 3 measurements from a variety of sensors.

The approach used in this tool allows the user to define an individual error threshold associated with each sensor. The error thresholds for each sensor measurement used in a fault check are then combined to yield a rule-specific error threshold.

3.5 Graphical User Interface

A Graphical User Interface (GUI) has been developed for the AFDD tool. The GUI has been built in Microsoft Excel using Visual Basic for Applications (VBA). This tool is very much a development tool which will be transitioned to a more scalable solution later in the project. The GUI allows the user to:

- Set up new AHUs in the AFDD tool;
- Modify set up parameters
- Visualise AFDD results

The GUI automatically generates a schematic of the AHU based on the components and sensors that are present within the unit. Users can select any particular instance of time to be presented on this schematic. This feature allows the user to quickly view a representation of the AHU under any past operating conditions allowing fault instances to be analysed in more detail.

All identified faults are listed by frequency of occurrence in the analysed period. Once a particular fault is selected, the GUI displays:

- The measured and virtual data on the schematic for the most recent hour in which the fault occurs
- A textual description of the currently displayed fault;
- A graphical trend of the past 48 hours of values relevant to that fault;
- Options to move to other instances of that particular type of fault in the analysed period;
- A list of possible diagnoses for the currently displayed fault;
- A list of other faults which occur during the same hour;
- The current operating mode of the AHU

This allows for rapid viewing of individual faults, but still requires partial user input to root cause the fault.

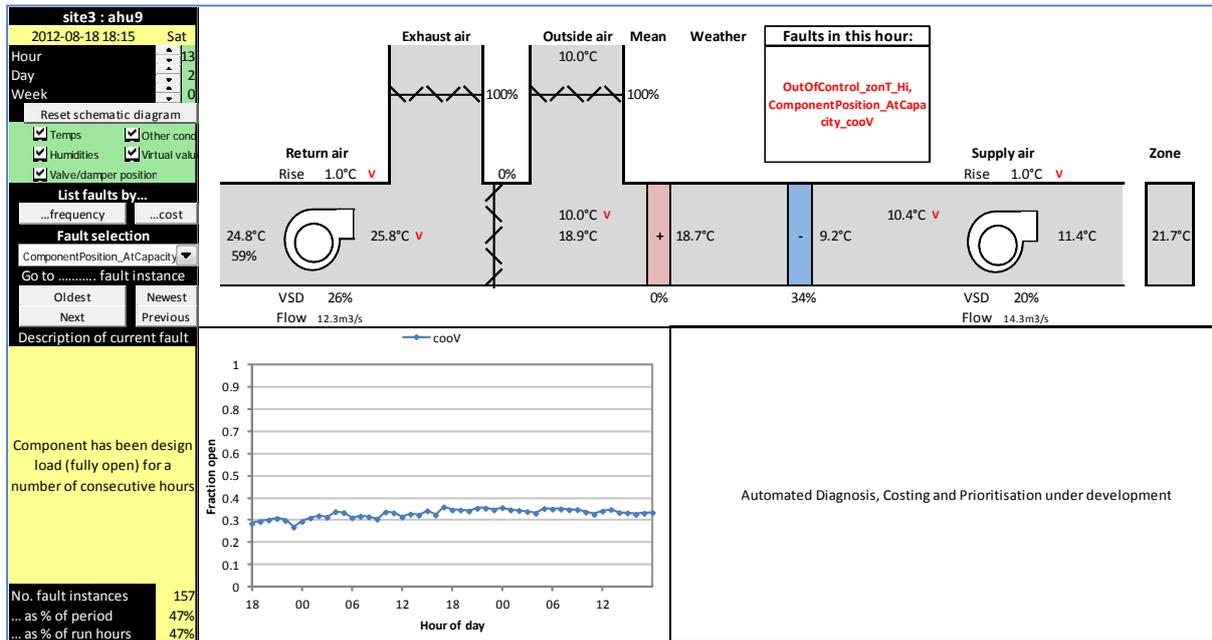


Figure 4: Screenshot of the GUI indicating an out of control zone air temperature

4. Pilot Study

4.1 I2E2

The Innovation for Ireland's Energy Efficiency (I2E2) Energy Technology Centre is an Irish government sponsored Centre. I2E2 was established to facilitate research that will have a direct impact on energy efficiency in industry internationally. The I2E2 research focus is on energy efficiency improvements in manufacturing processes and supporting systems. The current research agenda focuses on a number of areas of common interest to group members, one of which is HVAC systems. The original scoping of the HVAC project started in January 2009 and the project currently involves 2 research providers and 6 industry partners. The main objective of this research is to provide an automated FDD tool that has been extensively tested on a range of different AHUs across a number of disparate industrial sites

4.2 Pilot Study Outline

Several hundred AHUs were available for selection due to the scale of the industrial sites involved in this collaboration project. A number of characteristics were taken into consideration in order to select a number of representative units for the purpose of developing and validating the tool. As such, AHUs were selected with the following characteristics:

- Different component and sensor layouts in order to ensure that the AFDD tool can be applied effectively and comprehensively;

- Varying levels of instrumentation in order to alleviate concerns regarding the level of instrumentation needed to perform FDD effectively;
- The potential for duplication to ensure scalability to maximise savings.

In addition to the selection criteria, return air units with mixing boxes were selected as these are more complex than full fresh air units and hence have the potential for more faults. Furthermore, mixing units incorporate all the components and sensors found in full fresh air systems ensuring that, once proven for return air units, the AFDD tool could be relatively easily expanded to apply to full fresh air units. Figure 5 shows a picture of one of the pilot AHUs.



Figure 5: Picture of one of the pilot air handling units.

Table 2, in which the industry partners are anonymous, describes the major characteristics of each pilot AHU, which were selected to offer varying component and sensory distributions.

Table 2: Major characteristics of the pilot AHUs

| Site | No. of pilot AHUs | Type | Design maximum airflow [m ³ /s] | Supply fan motor power [kW] | Return fan motor power [kW] | Multi zone unit | Type of zone(s) supplied | Operating hours per annum |
|------|-------------------|------|--|-----------------------------|-----------------------------|-----------------|----------------------------|---------------------------|
| 1 | 2 | CAV | 14 | 30 | 15 | Y | Office & canteen | 8760 |
| 2 | 1 | CAV | 15 | Not available | Not available | N | ISO class 7 cleanroom area | 8760 |
| 3 | 4 | CAV | Not available | 45 | 22 | N | Production area | 8760 |
| 4 | 10 | VAV | 13 | 10 | N/A | N | Manufacturing Floor | 6240 and 3640 |
| 5 | 4 | VAV | 22 | 75 | 37 | Y | Office | 8760 |
| 6 | 1 | VAV | 14 | 45 | 25 | Y | Office | 3120 |

4.3 Results from pilot phase testing of the AFDD tool

4.3.1 General Observations

The most unexpected observation during the pilot study was the number of potential opportunities for improvement present in each of the pilot AHU's. The AFDD tool identified numerous physical and control system faults with all the units under analysis.

Manual interaction with the AHU's was identified as a major cause of energy inefficiency in the HVAC units under observation. Supply and zone set points were found to be manually adjusted to overcome what were actually ineffective control issues or physical faults in the system

There were significant difficulties encountered in obtaining data from the on-site BMSs due to a wide variety of issues. Most of these issues could be resolved by developing and using a standard that would provide a consistent naming convention for sensors and components and a normalised relational database schema for archiving long term BMS data. Unfortunately, to the best of the authors' knowledge, no such standard currently exists.

Aside from the issues in obtaining measured data, it was quite difficult to obtain design details of some AHUs. This was due to the age of many of the AHUs (resulting in a lack of documentation), frequent retrofits that have occurred on most sites (as the requirements for manufacturing environments change quite regularly), and difficulty in physically accessing the units in order to obtain measurements using temporary sensors and handheld devices.

4.3.2 Energy Savings identified by the AFDD tool

The AHUs on several of the sites have been analysed in detail using the AFDD tool and a number of faults have been detected. Table 4 provides an overview of the faults identified to date across the pilot AHU's and their associated costs which totalled over €121,000. These faults have been verified by physical inspection using airside measurements. The costs associated with the faults were estimated assuming conservative annualised unit costs of associated energy.

Table 3: Savings identified to date.

| Site | No. of AHUs investigated | Faults identified by the FDD tool | Annual savings opportunities (approx) | Verification method |
|------|--------------------------|-----------------------------------|---------------------------------------|--|
| 1 | 2 | Passing heating coils | €18k | Physical (airside) survey by the authors |

| | | | | |
|---|---|--|------|---|
| 3 | 4 | Damaged dampers, low supply temperature, passing cooling coil | €23k | Physical (airside) survey by the authors |
| 4 | 4 | Damaged dampers | €3k | Physical (airside) survey by the authors |
| 5 | 4 | Poor design, passing frost coils & incorrect set-points | €14k | From extensive BMS data and confirmed independently |
| 6 | 1 | Passing heating coil, poor frost protection control setup, leaking dampers | €3k | Independent physical survey |

5. Future work

Currently, the business layer of the AFDD tool is procedural in design. While this was appropriate in order to rapidly test the initial FDD method for a limited number of AHUs, this approach is not effective on varying types of AHU's. Therefore, the next step is to redevelop the business layer using an object-oriented approach to allow its expanded and scalable use across all types of AHU's. In conjunction with this work, further capabilities will be added to consider different types of faults, such as fan, motor, filter and variable frequency drive (VFD) faults using the pressure, power, and flow sensor data that is available in many of the AHUs.

Other future work will focus on further validation of the savings using an established international standard for measurement and verification such as ASHRAE Guide 14[16] of the International Measurement and Verification protocol (IPMVP) [17].

Fully automated fault diagnosis is the key next step in the project. As described earlier, users must currently manually diagnose the root-cause of a particular fault given a number of suggested possibilities. A method to fully automate this process is currently under testing in conjunction with the development of a method of prioritisation to aid end users in selecting which faults to repair first.

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